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DIRECT MEASUREMENTS OF INTERPLANETARY MAGNETIC FIELD AND PLASMA

NORMAN F. NESS

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

To be presented at IQSY/COSPAR Symposium July 18, 1967 Imperial College, London, England

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Direct measurements on satellites and space probes since 1961 have demonstrated the existence of the solar wind, essentially as theoretically predicted by E. N. Parker. Typical values at 1 A.U. of the interplanetary magnetic field are: 6 gamma average magnitude ranging between 2 to 40 gamma; flux values range from 10^8 to 10^{10} ions/cm^2/sec. Additional first order results suggest that the solar wind source is located at 10° to 25° north heliographic latitude and appears (at 1 A.U) to come from approximately 1.5° east of the sun, a direct result of corotation of the inner solar corona. Synoptic studies of physical properties have indicated a sectoring of the direction of the interplanetary magnetic field and correlated variations of plasma velocity, density and temperature. Second order results recently obtained reveal a fine scale filamentary structure of the interplanetary magnetic field which directly connects to the sun. Field aligned thermal (or random velocity) anisotropies in the solar plasma are also observed. This paper reviews the quantitative results and synoptic picture which has emerged of the extended solar corona as observed from 0.7 to 1.5 AU during the last six years by the Mariner, IMP, Pioneer and Vela spacecraft.

Introduction

The physical properties of the interplanetary medium were not experimentally accessible until 1959. At that time, the satellite era, initiated in 1957 by the USSR Sputnik, had progressed so that launching of instruments into deep space permitted in situ studies. Prior to this, the properties of the interplanetary medium were studied by a number of indirect methods.

The analysis of geomagnetic disturbances following solar flare occurrences and the analysis of energetic particle bombardment of the terrestrial surface yielded information concerning the modulation of cosmic rays for the subsequent development of models of the interplanetary medium. In addition, studies of the solar atmosphere in the vicinity of the sun were performed by observing the scintillation of stars. Various other techniques investigated the scattering and refractive effects of the interplanetary medium on electromagnetic radiation.

Generally it was thought that interplanetary space was approximately a perfect vacuum with only some residual neutral dust particles present in possibly a static atmosphere of the sun. In a series of studies beginning in 1957, E. N. Parker developed a theory of the hydrodynamic expansion of the solar corona into interplanetary space. Inherent in this model is the extension of the solar magnetic field as observed in the photosphere and the development of a characteristic Archimedean spiral geometry due to the rotation of the sun. At 1 A.U. $\vec{B}$ is oriented generally in the plane of the ecliptic (inclined 7° to the heliographic equator) and is directed on average at 45^{o} to a solar radius vector in a sense either outwards from the sun or inwards to the sun. Many features of the cosmic ray terrestrial observations were explained reasonably well by this general model and today this theoretical work has withstood the test of detailed critisism and the direct measurements by experimental apparatus. It is not the intent of this paper to review the theoretical model but rather to review the experimental observations and results obtained concerning the detailed physical properties of the interplanetary plasma and its magnetic field. Space limitations will preclude expansive discussions of any one result and specific comparison with theoretical treatments. Interested readers are referenced to the text by Parker (1963) for a summary of the status prior to these direct measurements. This paper presents results generally in chronological order according to launch schedule and not subsequent analyses and publication of conclusions which may in fact have occurred several years later.

As a result of experimental studies there are certain general features of the interplanetary medium which have been identified. The solar wind is a flux of plasma, the principal positive ionic constituent being hydrogen, with approximately 5% helium and is measured at 1 AU to be between 10^{8} to 10^{10} ions/cm^{2}/sec with an average energy of 1 KEV/ion. Threading through the plasma is the interplanetary magnetic field, of solar origin, with an average magnitude of 6 gamma at 1 AU although fluctuations occur with magnitudes between 2 to 40 gamma, largest when following solar flare activity. The solar wind appears to flow from slightly east of the sun by 1.5°, an effect which is identified with the corotation of the solar corona out to several solar radii beyond the sun. The longitudinal structure and temporal permanency of specific features lead to an apparent corotation of characteristic time variations of the interplanetary medium when observed by satellites and space probes between 0.7 and 1.5 AU. It is emphasized that this more distant corotation is an apparent feature and does not imply the rigid rotation of the more distant interplanetary medium with the sun.

From details available from satellite studies it is convenient to consider the structure of the interplanetary medium on three time scales:

1. Micro-structure (less than one hour) which includes shock waves and plasma-magnetic field discontinuities;
2. Meso-structure (one to 10^2 hours) which includes filaments or kinks in the field topology and;
3. Macro-structure (greater than 10^2 hours) which refers to the sectoring of the interplanetary medium and very long filaments.

These time scales may be converted to length scales at 1 AU by multiplying by an average solar wind velocity of 400 km/sec. These then yield:

1. $L_{\mu s} < 10^6 \text{ km} \doteq 0.01 \text{ AU}$
2. $L_{meso} \approx 10^{6-8} \text{ km} \doteq 0.1 \text{ AU}$
3. $L_{macro} > 10^8 \text{ km} \doteq 1 \text{ AU}$

PRE IQSY Results

Early measurements in 1961 of magnetic fields and plasmas by Explorer 10 in the earth's magnetosheath (Heppner et. al., 1963 and Bonetti et. al., 1963) and of the permanent distortion of the geomagnetic field by Explorer 12 (Cahill and Amazeen, 1963) suggested the permanent existence of the solar wind as modeled by Parker. Early USSR results by Gringauz et. al., (1960) measured a low energy plasma flux on Luna 2. However it was not until the US Venus probe, Mariner II, conducted an extended series of measurements at the end of 1962 that direct detection of the interplanetary plasma and analysis of its characteristics was possible. A summary of the average properties of the positive ion component of the solar wind has been given by Neugebauer and Snyder (1966) and figure 1 presents their results obtained over the five solar rotations 1767-1771 in 1962. The data are presented on a 27 day time scale so that the recurrence of high velocity plasma streams, another of the major early results obtained with this experiment, are readily identified. It is seen that the number density and velocity frequently vary 180° out of phase so that flux values are more constant than either density or velocity. For these data an average velocity $\overline{v}$ of 504 km/sec is obtained with $\overline{n}_p = 5$ and the fractional helium content as $4.6 \pm 3.8\%$, with $V_{He}tt \doteq V_H t$. The study of the spatial gradient of the flux of interplanetary plasma is shown in figure 2 and is compared with the theoretical model of Parker. The plasma velocity was observed to be essentially independent of distance from the sun for distances between 0.7 - 1.0

AU. The density, flux and energy density show good agreement with theory, which predicts an inverse distance squared dependence.

Studies of the interplanetary magnetic field by Smith (1964), and Davis et. al., (1966) revealed the general agreement of the observations with the Archimedean spiral model of Parker. Earlier observations of the interplanetary magnetic field by Pioneer V had suggested a general dipolar field (Coleman et. al., 1960) although recently Greenstadt (1966) has reviewed these data and showed that now they compare favorably with the model of Parker. Detailed analysis of the fluctuations of the interplanetary magnetic field have been performed by Coleman (1966) and a sample of the results obtained is shown in figure 3. The fluctuations of the component of the magnetic field parallel to a solar radius vector is studied for time scales from 74 seconds to 1 day. The predominant feature of the spectrum is the inverse frequency dependency, which is due principally to the presence of numerous small abrupt discontinuities in the interplanetary magnetic field. The spectrum, its changes and characteristic values are important in both the microscopic properties of the interplanetary medium and the propagation of cosmic rays through the solar system.

Since $$\left.\frac{dB_i}{dt}\right|_{\text{observed}} = \frac{\partial B_i}{\partial t} + (\vec{V}_{sw} \cdot \nabla)\, B_i$$

and the solar wind velocity, V_{sw}, is larger than the MHD wave velocities by a factor of 5-10, the second term on the RHS is correspondingly larger than the first. Thus, convection of the interplanetary plasma past a satellite or space probe dominates the measurement of fluctuations so that the actual temporal variations of the interplanetary magnetic field have not yet been studied.

IQSY Results

Extended measurements of the interplanetary plasma on an earth orbiting satellite were first accomplished by IMP-1 at the end of 1963 and early 1964 (Bridge et. al., 1965; Wolfe et. al., 1966a). Accurate measurements of the interplanetary magnetic field were obtained (Ness et. al., 1964) with the distribution of average magnitudes over 3 solar rotations shown in figure 4. The vector properties of the interplanetary field showed characteristic patterns paralleling the expected Archimedean spiral angle, and at either a positive ($\phi \sim 135^{\circ}$) or negative ($\phi \sim 315^{\circ}$) sense at 1 AU. The observed distribution parallel and perpendicular to the ecliptic plane are shown in figure 5. It is noted that there appears to be a small average southward component to the interplanetary magnetic field perpendicular to the ecliptic, which was previously observed by Mariner II and Pioneer 5. The physical inconsistencies inherent in such a permanent magnetic field component have recently been reviewed by Dessler (1966). The average field magnitude is observed to be 6 gamma and the distribution indicates the permanent existence of an imbedded magnetic field threading through the interplanetary plasma. The correlation of photospheric magnetic field directions with the interplanetary magnetic field demonstrates the solar origin and extension into interplanetary space (Wilcox and Ness, 1966).

The magnetic field direction, correlated with photospheric magnetic field measurements yielded a 4.5 ± 0.5 day delay time from the central meridian passage. This leads to a solar wind velocity of

385 $\pm$ 45 km/sec., (Ness and Wilcox, 1964) and is in good agreement with the direct measurement of average plasma velocity of 378 km/sec (Wolfe et. al., 1966). Studies of the recurrence character of the field direction as well as comparison with the photospheric magnetic field direction utilizes correlation function techniques. These correlative studies and coherent results established the solar origin of the interplanetary magnetic field and also revealed the longitudinal structuring of the field polarities into constant polarity sectors during this time (Ness and Wilcox, 1965). The 4 sectors deduced from the IMP-1 data are shown in figure 6 in which a circular superposed epoch map is presented for the interplanetary magnetic field directions measured during the three solar rotations 1783-1785. The correlation of cosmic ray "streams" contained with a specific sector during these same 3 solar rotations is shown in figure 7 using data from the University of Chicago experiment (Fan et. al., 1965). These data are presented on a 27 day basis with the overlay of the sectors, determined from the magnetic field data, and show a remarkable correlation as well as evidence of distortion of a rigid sector pattern associated with a magnetic storm disturbance (Wilcox and Ness, 1965).

In addition to identifying recurrent structures within the interplanetary field at 1 AU these correlation analyses also yield characteristic periodicities which can be compared with synodic rotation periods of photospheric fields at different heliographic latitudes. Figure 8 compares the periodicities of rotation of photospheric magnetic fields and the IMP-1 period with the study of sun spot periods by Newton and Nunn (1951) demonstrating the differential rotation of these features. These data, when correlated with additional coronal information suggest that the solar plasma as observed during this time had an origin at roughly 10° to 20° north heliographic latitude (Wilcox and Ness, 1967). Subsequent studies in the IMP satellite series have confirmed and permitted a tracking of the latitude source of solar plasma as deduced from the recurrence periods of the sector structure.

A summary of the measurements of sector structure beginning in 1962 and continuing to IMP-3 in 1965 is shown in figure 9. The quasi-stationary character of the four sector structure observed in late 1964 as measured by IMP 2 (Fairfield and Ness, 1967) is clearly evident in this figure. The break-up of this regular pattern in 1965, detected by Mariner IV (Coleman et. al., 1967) and IMP-3 (Ness and Wilcox, 1967) is also clear. The autocorrelation analysis of the IMP-3 1965 data yields recurrence periods of the polarity patterns of 28 days which suggests the solar wind origin was at an even higher latitude, approximately 20° - 25°, than for IMP-1 (Ness and Wilcox, 1967). During 1965, the sector pattern was evolutionary with new sectors appearing and others disappearing.

Definitive measurements of the positive ion spectrum have been obtained in the Vela satellite program by a group at the Los Alamos Laboratories (Hundhausen et. al., 1967a). A sample of data obtained during 1965 with very closely spaced windows measuring the energy per unit charge spectrum and directional characteristics of the interplanetary plasma is shown in figure 10.

A detailed study of the direction of arrival of the plasma on the Vela-2 satellite by Strong et. al., (1967) indicates an angular departure of radial flow of solar plasma approximately 1.5^{o} east, in the sense of a rigidly corotating inner solar corona. These results are in good agreement with the theoretical studies by Weber and Davis (1967) and observational studies of cometary tail orientations by Brandt et. al., (1966). The consequences of the net torque exerted on the sun for geological time scales has been pointed out by Brandt (1966).

Detailed studies of the velocity distribution function have been performed in the Vela series of satellites by Hundhausen et. al., (1967a). Figure 11 presents a two-dimensional map of the velocity of the interplanetary plasma with contour lines of flux values at 10% increments of the maximum. The average bulk velocity is indicated by a solid triangle near the center of the map. The non-circular symmetry of the velocity distribution function indicates an equivalent temperature anisotropy of the random motions. Superimposed on these data is the direction of the interplanetary magnetic field. The instantaneous alignment of the thermal anisotropy of the solar plasma with the interplanetary magnetic field, as demonstrated here, is due to the conservation of the first adiabatic invariant of the solar plasma as it flows outward from the sun. An extended comparison of simultaneous data obtained on two different earth orbiting satellites, Vela-3 and IMP-3, are presented in figure 12. These data show the generally excellent agreement between the predicted magnetic field direction as deduced from the temperature anisotropy with the measured interplanetary magnetic field (Hundhausen, Bame and Ness, 1967).

The results from the IMP and Vela satellites generally have been the principal contributors during the IQSY to our understanding of the physical parameters describing the interplanetary medium. Both macro-structure: the sectoring of the interplanetary medium; and the micro-structure of the temperature anisotropy of the interplanetary medium, were detected and identified.

Important Results: 1966-1967

Just as the close of IQSY, December 1965, the US launched the Pioneer 6 interplanetary probe to study the plasma,cosmic rays and magnetic fields between 0.8 and 1 AU. Data were obtained essentially continuously over 6 solar rotations from December 1965 to May 1966, 1811-1817, with subsequent sporadic data obtained thereafter. The important feature of Pioneer 6 data is that it was obtained on the ascending phase of solar activity. Evidence of this is seen in figure 13 in which the magnitude distribution function of hourly averages is shown yielding a median of 5 gamma although there were several intervals during which the average magnetic field exceeded 16 gamma for more than 1 hour. These large field strengths are characteristically associated with intense solar flare disturbances. The directional distribution function for the interplanetary magnetic field is shown in figure 14. Here it is noted that the Archimedean spiral again is a characteristic feature of the component projected on the ecliptic plane but there is no detectable average component perpendicular to the ecliptic plane.

A study of the recurrence period for Pioneer 6 yields a peak at 29 days. On this time scale the polarity sector structure is presented in figure 15 and it is noted that an evolutionary pattern is readily evident. The sectors are non-stationary although there appear to be roughly 4 sectors as previously observed. This apparent permanency of 4 sectors throughout these satellite studies may reveal a heretofore unanticipated longitudinal pattern of the internal structure of the sun.

Since the Pioneer 6 satellite moves differentially with respect to the earth in heliocentric radial distance and longitude, the correction for corotation of significant interplanetary features yields a period of approximately 28 days. This recurrence period is longer than obtained on the IMP-1, but is similar to IMP-3 and suggests that the source solar plasma is still north of the solar equator, by as much as 20^{o} to 30^{o} for this time interval. Simultaneous measurements between Pioneer 6 and IMP-3 (Ness, 1966) have been compared when the two satellites were in the vicinity of the earth but separated by 1×10^{6} kilometers. The data, when time shifted by approximately one hour, showed excellent agreement in both magnitude and direction. This demonstrates the local uniformity of the interplanetary magnetic field on length scales of 0.01 AU.

The satellite study of solar cosmic ray anisotropies and the interplanetary magnetic field has been initiated by McCracken and Ness (1966). In this work the direction of arrival of solar cosmic rays was compared with the direction of the instantaneous interplanetary magnetic field. Figure 16 presents this comparison and shows the feature of collimation of the cosmic rays by the interplanetary magnetic field. This fine scale feature has been observed in subsequent studies of cosmic ray anisotropies. Statistically it has been shown (McCracken, Rao, and Ness, 1967) that cosmic ray anisotropies can be separated into two classes: <u>non-equilibrium</u> and <u>equilibrium</u>. Immediately following solar flare injection, the solar cosmic ray anisotropy (20-50%) is well aligned with the local interplanetary magnetic field. This indicates the firm rooting of interplanetary magnetic field lines to the sun where particles are injected and their subsequent propagation to the space probe. The equilibrium anisotropy appears late following a flare event and persists during quiet times and is characterized by a temporal invariance of both the magnitude (5 to 10 percent) and phase of the anisotropy with the maximum observed coming from the solar direction. Thermal anisotropy of the solar plasma has also been observed (Wolfe et. al., 1966b).

A radial gradient to the interplanetary magnetic field has been detected by Burlaga and Ness (1967) and shown to be in general agreement with the model of Parker in which the transverse component and radial component of the magnetic field decrease approximately proportional to distance and distance squared, respectively. In addition a detailed study of discontinuities, characterized by abrupt transient decreases in the magnitude of the magnetic field suggests that this class of microstructure corresponds to a tangential discontinuity and is not identified as a shock, or a rotational discontinuity.

These are discontinuities which probably act as discrete thin cosmic ray scattering centers with length scales of 1×10^4 kilometers. The general model of the microscopic structure of the interplanetary medium which results from the observations of numerous tangential discontinuities is that the interplanetary filaments or flux tubes identified by Ness, Scearce and Cantarano (1966) are more appropriately considered to lie atop one another like "noodles on a plate" (Burlaga and Ness, 1967).

Relationship of K_p to Interplanetary Medium

Studies of the variation of the planetary magnetic activity indices K_p and a_p with solar wind velocity have been carried out by Snyder et. al., (1963), Maer and Dessler (1964), and Hirschberg (1965). The general result obtained is that K_p increases with a rise in velocity although the exact analytical relationship between them is subject to some discussion. Dessler and Fejer (1963) had proposed that K_p would depend upon the rate of change of solar wind pressure. The interplanetary magnetic field is also an important factor in affecting K_p. Dungey (1961) initially suggested that in the presence of a southward directed interplanetary magnetic field, terrestrial magnetic activity would be enhanced due to reconnection of geomagnetic and interplanetary field lines. Fairfield and Cahill (1966) and Fairfield (1967) have tested and substantiated this hypothesis with data from Explorer XII and IMP-2. In addition, to such directional dependencies, the magnitude of the interplanetary magnetic field has been correlated with K_p for IMP-1 and IMP-3 data by Wilcox et. al., (1967) and Schatten and Wilcox (1967). Statistically, as shown in figure 17, it is found that K_p (or a_p) is approximately a linear function of field magnitude.

Summarizing:

$$\left\{\begin{array}{llll} V_{sw} = 8.44\ K_p + 330 & \text{(Km/sec)} & & \text{(SN\&R)} \\ V_{sw} = 290\ a_p^{\ 0.22} & \text{(Km/sec)} & & \text{(M\&D)} \\ V_{sw} = 269 \log a_p + 222 & \text{(Km/sec)} & & \text{(H)} \end{array}\right.$$

$$\begin{cases} K_p = (0.33 \pm 0.02)\ |\vec{B}| \pm 0.2 & \text{(WS\&N)} \\ a_p = (1.5 \pm 0.1)\ |B| + 0.7 \pm 0.5 & \text{(S\&W)} \end{cases}$$

Summary and Prognosis

The measurement of low energy plasmas and very low level magnetic fields on satellites and space probes has progressed very far since 1959. Experimental techniques now permit the fabrication of non-magnetic spacecraft so that vector magnetic fields can be measured to accuracies of ± 0.2 gamma. In addition, communication rates of data from experiments has increased so that additional fine time scale and thus spatial details of the interplanetary medium can be studied.

The direct measurement of the interplanetary plasma and its imbedded magnetic field during the past several years has verified the theoretical model developed principally by Parker. Detailed measurements reveal a morphology in which the permanent longitudinal structure of the solar plasma and magnetic field at the solar surface is reflected in an apparent corotation of spatial structure observed between 0.7 and 1.5 AU. The interplanetary magnetic field is identified to be of solar origin and to result from the extension of photospheric fields into interplanetary space by the solar plasma. Gradients of the interplanetary plasma and magnetic field have been observed in good agreement with the classic solar wind model. Microscale structure of the interplanetary medium shows the alignment of plasma thermal anisotropies with the instantaneous magnetic field and the meso-scale feature of collimation of solar cosmic rays along the interplanetary magnetic field immediately after injection. The macroscale sector structure of the interplanetary magnetic field reveals longitudinal variations of the corona which persist over several solar rotations.

Measurements of the plasma have been made only on the positive ionic portion. The detection of electrons in the solar wind has been attempted by observing the effect on radio waves propagated through the interplanetary medium. A summary of solar wind physical properties observed at 1 AU between 1962-1966 is given in Table II.

In the initial phases of exploration of the interplanetary medium separate results from individual experiments were very important. It is now clear that the correlation of plasma, magnetic field and particle measurements is essential to definitively establish the physical parameters of the interplanetary medium as well as to understand their characteristic temporal variations.

The intrinsic difficulties in the measurements of the electron component of the plasma are due to the modifications present when the spacecraft itself is imbedded within the plasma. It may be sometime before "hard" experimental results are obtained on this important element of the solar plasma. Definitive studies of plasma stability and wave propagation will not be conducted until the distribution function for the electrons is as well known as that for the position ion component. By measurements not only of energy per unit charge but also mass/unit charge (as conducted on Explorer 34 by Ogilvie et. al., 1967) will definitive measurements on the chemical composition of the solar plasma be obtained. Finally, there are extensive experimental data already received which have yet to be analyzed due to difficulties in processing large quantities of data. The analysis of these data by the scientific community has required substantially more time than for real time transmission of the raw data. The continued analysis of such data will contribute additional observational information to the present set of experimental facts.

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TABLE 1

SATELLITE	LAUNCH DATE	ORBIT (Geocentric Apogee)	LIFETIME IN DAYS	PLASMA-MAGNETIC FIELD INSTRUMENTATION
Luna 1	1-2-59	Solar Orbit	1	Electron-Ion Trap
Luna 2	9-12-59	Luna Impact	1.5	Electron-Ion Trap
Pioneer V	3-11-59	Solar Orbit (0.9→1.0 AU)	50	Search Coil Magnetometer
Explorer 10	3-25-61	Apogee = 42.6 R_E	2.2	Faraday Cup; Fluxgate, Rubidium Vapor Magnetometers
Mariner II	8-27-62	Venus Flyby (0.7→1.0 AU)	128	Electrostatic Analyzer; Fluxgate Magnetometer
IMP-1	11-27-63	Apogee = 31 R_E	181	Electrostatic Analyzer, Faraday Cup; Rubidium Vapor, Fluxgate Magnetometers
Vela 2A, 2B	7-17-64	Circular ~ 17 R_E	S.O.	Electrostatic Analyzer; Search Coil Magnetometer
OGO-1	9-5-64	Apogee = 24.3 R_E	S.O.	Similar to IMP-1
IMP-2	10-4-64	Apogee = 15.9 R_E	150	Same as IMP-1
Mariner IV	11-28-64	Mars Flyby (1.0→1.5 AU)	270	Faraday Cup; Helium Vapor Magnetometer
IMP-3	5-29-65	Apogee - 40 R_E	720	Same as IMP-1
Vela 3A, 3B	7-20-65	Circular ~18.5 R_E	S.O.	Electrostatic Analyzer; Search Coil Magnetometer
Pioneer 6	12-16-65	Solar Orbit (0.81→0.98 AU)	200 S.O.	Electrostatic Analyzer; Faraday Cup; Fluxgate Magnetometer
Luna 10	3-31-66	Lunar Orbit	60	Electron-Ion Trap; Fluxgate Magnetometer
OGO-3	6-6-66	Apogee = 24 R_E	S.O.	Same as OGO-1
Explorer 33	7-1-66	Apogee = 81 R_E	S.O.	Faraday Cup; Fluxgate Magnetometers

TABLE 1 (Continued)

SATELLITE	LAUNCH DATE	ORBIT (Geocentric Apogee)	LIFETIME IN DAYS	PLASMA-MAGNETIC FIELD INSTRUMENTATION
Pioneer 7	8-17-66	Solar Orbit (1.0→1.1 AU)	S.O.	Same as Pioneer 6
Vela 4A, 4B	5-10-67	Circular ~17 R_E	S.O.	Electrostatic Analyzer
Explorer 34	5-24-67	Apogee = 31 R_E	S.0	Electrostatic and Magnetic Analyzer; Fluxgate Magnetometer

TABLE 1 - Summary of US and USSR satellites and space probes which have provided experimental data on the interplanetary plasma and magnetic field.

TABLE II

	Minimum	Maximum	Average
Flux (ions/cm^2/sec)	10^8	10^{10}	$3x10^8$
Velocity (Km/sec)	280	900	400-500
Direction of Flow	$\pm 10^o$	of Solar Radius Vector	-1.5^o East
Density (ions/cm^2)	0.4	80	5
% Helium/Hydrogen	0	15	4
Temperature (^oK)	$6x10^3$	$1x10^6$	$2x10^5$
Thermal Anisotropy (T_{max}/T_{ave})	1.0 (isotropic)	2.5	1.4
Magnetic Field Magnitude (gamma)	0.25	40	6
Magnetic Field Direction (wrt Solar Radius Vector)	in ecliptic plane		135^o,315^o
Magnetohydrodynamic Wave Phase Velocities (Km/sec)	30	150	60

Summary of Average Properties of Interplanetary Medium observed at 1 AU during 1962 - 1966

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FIGURE CAPTIONS

Figure 1 3 Hour Average values of plasma velocity V and proton number density n_p (logarithmic scale) as observed by Mariner II in 1962. (Neugebauer and Snyder, 1966).

Figure 2 Measured gradient of proton number density n_p, flux $n_p V$ and energy flow by Mariner II with comparison to inverse distance squared theoretical dependence (Neugebauer and Snyder, 1966).

Figure 3 Power spectrum of radial component of interplanetary magnetic field fluctuations observed by Mariner II (Coleman, 1966).

Figure 4 Magnitude histogram of interplanetary magnetic field observed by IMP 1 in 1963-1964

Figure 5 Directional distribution function of interplanetary magnetic field observed by IMP-1 in 1963-1964 (Ness and Wilcox, 1964).

Figure 6 Characteristic sector structure of interplanetary magnetic field observed by IMP-1 in 1963-1964 (Ness and Wilcox, 1965).

Figure 7 Consecutive 27 day periods of observations of persistent solar cosmic ray flux on IMP-1 indicating confinement to a single sector for three solar rotations. (Wilcox and Ness, 1965).

Figure 8 Apparent rotation period of photospheric magnetic fields sun spots and autocorrelation-deduced period for interplanetary magnetic field at 1 AU as observed by IMP-1 as function of heliographic latitude (Ness and Wilcox, 1964).

Figure 9 Summary of Mariners II and IV, and IMP's 1, 2 and 3 determinations of the interplanetary sector structure from 1962-1966. The boundaries and polarity are indicated and superimposed on the C9 diagram of magnetic activity for this period (Ness and Wilcox, 1967).

Figure 10 Typical Vela 3 spectrum (counts versus energy per unit charge in a fixed direction) and the associated angular distribution (counts versus direction, $\phi = 180^{\circ}$ is anit-solar, at a fixed energy per unit charge.) Hundhausen et. al., 1967a).

Figure 11 A contour mapping in the V_1 V_2 plane of a typical proton velocity distribution function derived from Vela 3 data. The small triangle indicates the mean velocity. $\vec{B}_p$ indicates the IMP-3 5.46 minute average magnetic field direction as projected onto the V_1V_2 plane for the time interval centered at 0448 UT. (Hundhausen et. al., 1967b).

Figure 12 The magnetic field direction ϕ_b and direction of maximum proton temperature ϕ_a, plus 180° (measured on Vela 3B) for a six hour period on 4 August 1965. (Hundhausen, et. al., 1967b).

Figure 13 Magnitude distribution function for interplanetary magnetic field observations by Pioneer 6 in 1966.

Figure 14 Direction distribution function for Pioneer 6 interplanetary magnetic observations in 1966 (Burlaga and Ness, 1967).

Figure 15 Summary of polarity directions of the interplanetary magnetic field observed by Pioneer 6 during consecutive 29 day periods (Burlaga and Ness, 1967).

Figure 16 Comparison of interplanetary magnetic field and solar cosmic ray anisotropic directions projected onto ecliptic plane (McCracken and Ness, 1966).

Figure 17 Scatter plot of three-hour K_p values versus three-hour average values of the interplanetary magnetic field magnitude for IMP-1. The small open circles represent the original data and the solid circles as averages of contiguous 10% segments of the data, according to magnitude ordering. The open triangles represent IMP-3 data, for which there were approximately four times as much data. (Schatten and Wilcox, 1967).

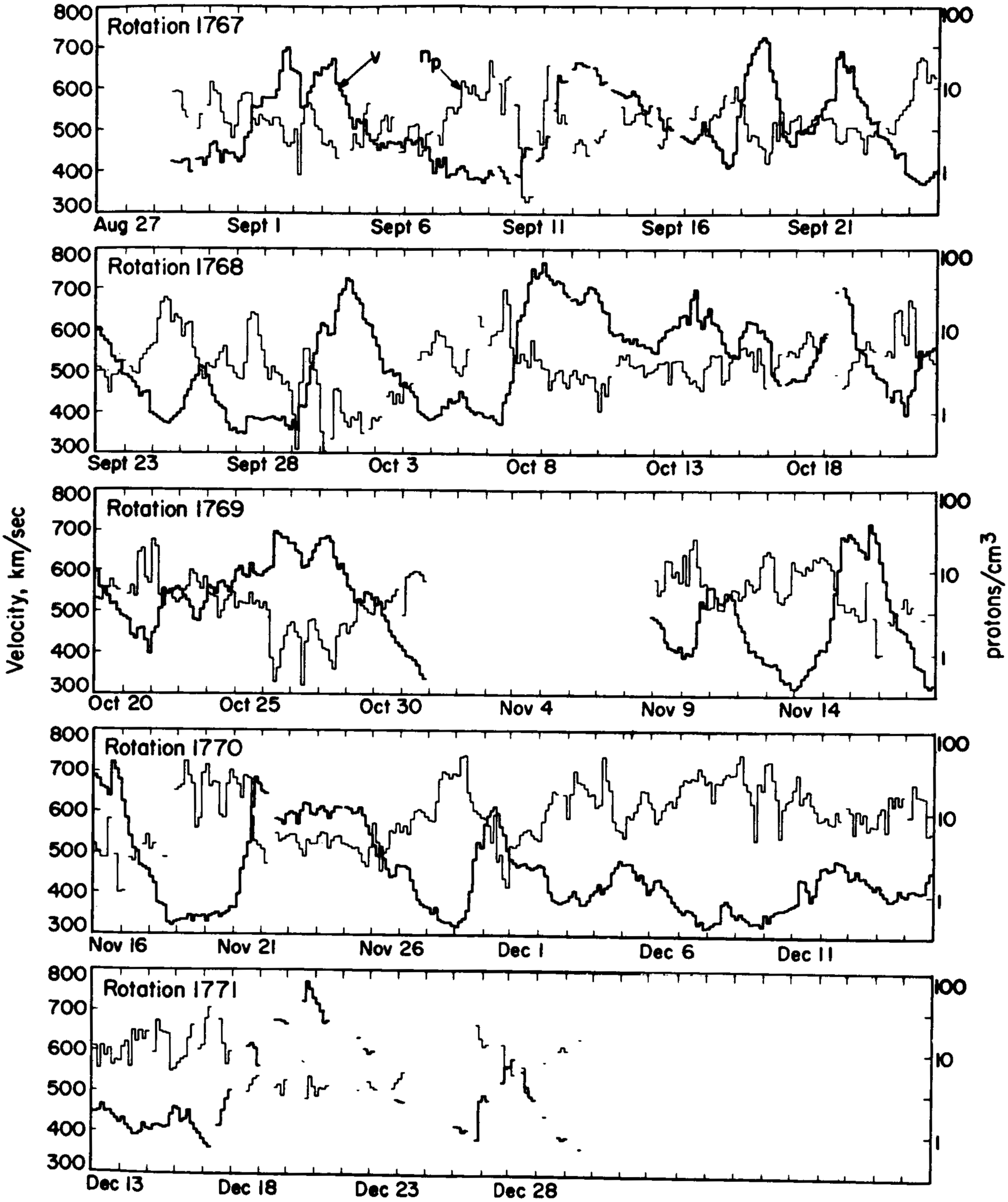
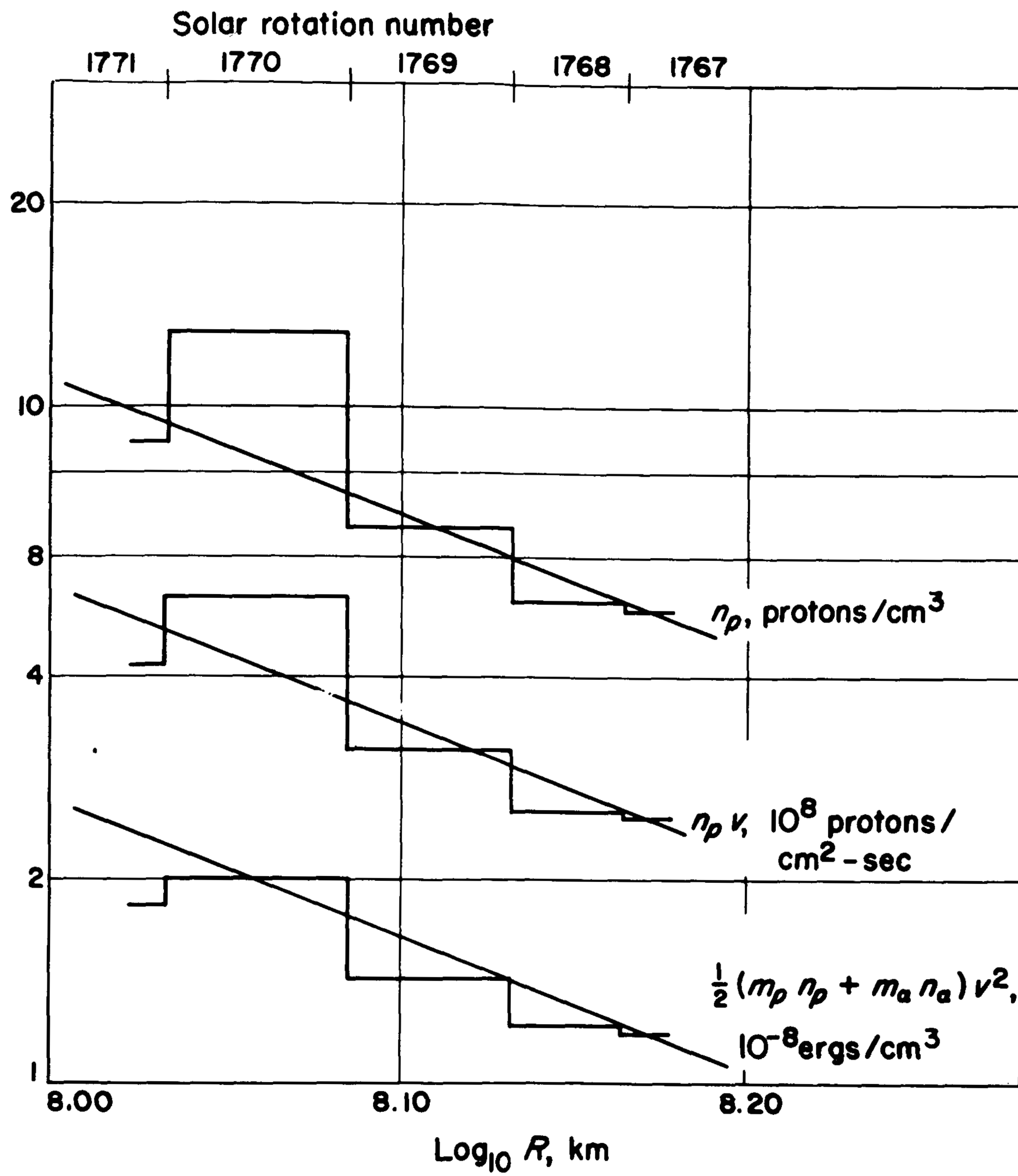
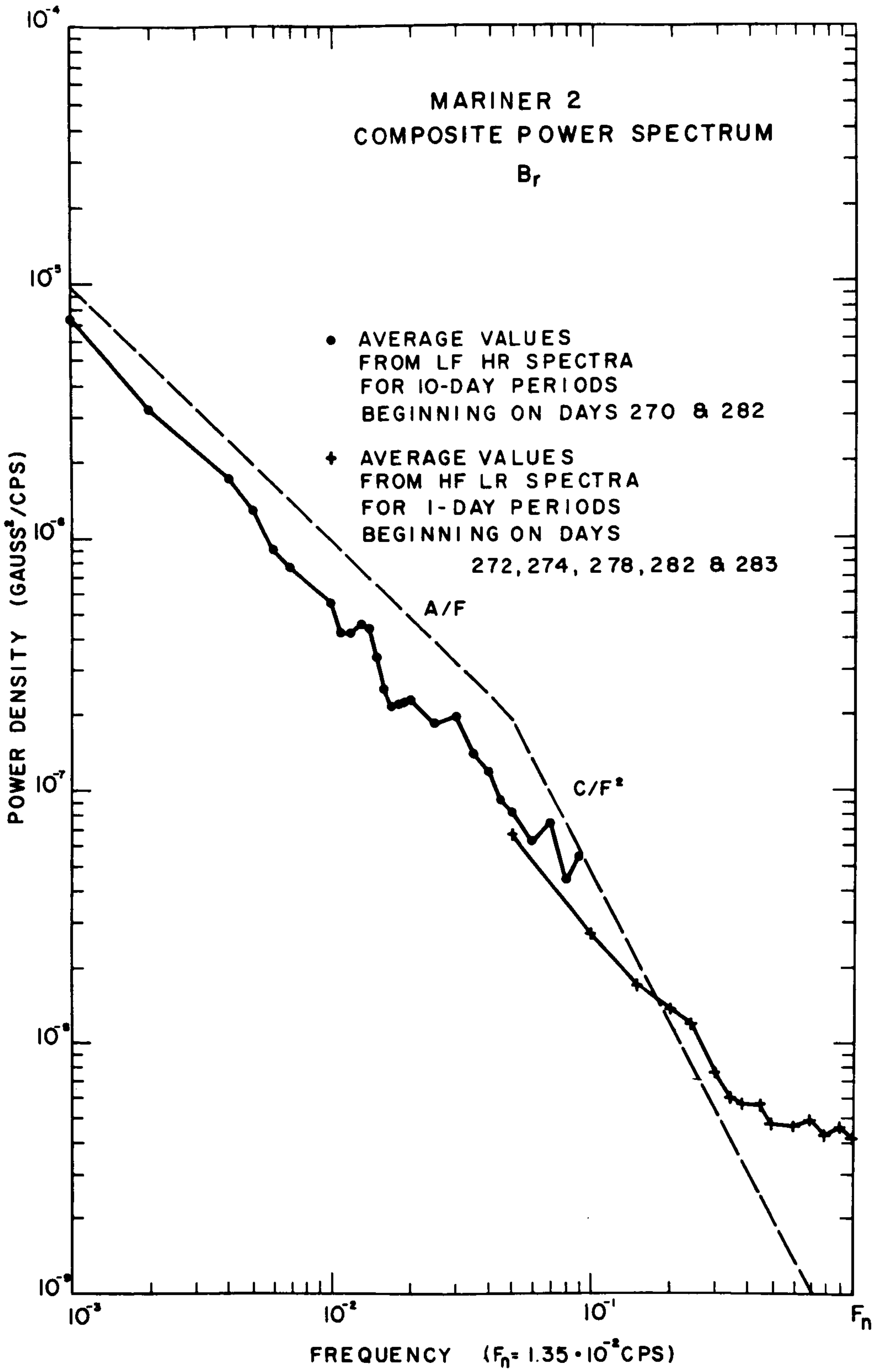

Rotation 1767
Rotation 1768
Rotation 1769
Rotation 1770
Rotation 1771
v
n_p
Velocity, km/sec
protons/cm3
800
700
600
500
400
300
100
10
1
Aug 27
Sept 1
Sept 6
Sept 11
Sept 16
Sept 21
Sept 23
Sept 28
Oct 3
Oct 8
Oct 13
Oct 18
Oct 20
Oct 25
Oct 30
Nov 4
Nov 9
Nov 14
Nov 16
Nov 21
Nov 26
Dec 1
Dec 6
Dec 11
Dec 13
Dec 18
Dec 23
Dec 28

FIGURE 1



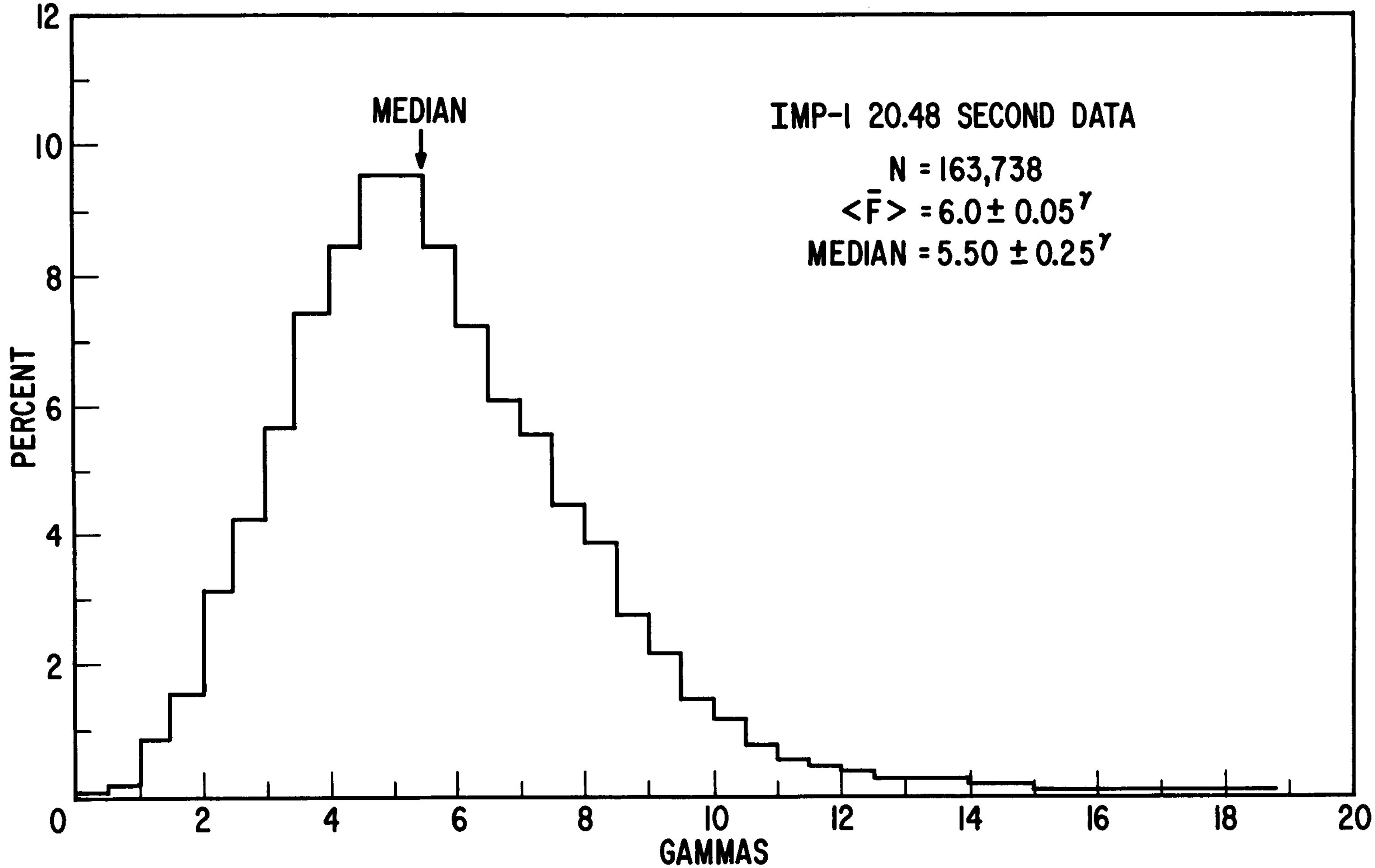
Solar rotation number
1771
1770
1769
1768
1767
20
10
8
4
2
1
n_p, protons/cm^3
$n_p v$, 10^8 protons/cm^2-sec
$\frac{1}{2}(m_p n_p + m_\alpha n_\alpha) v^2$, 10^{-8} ergs/cm^3
8.00
8.10
8.20
$\log_{10} R$, km

FIGURE 2



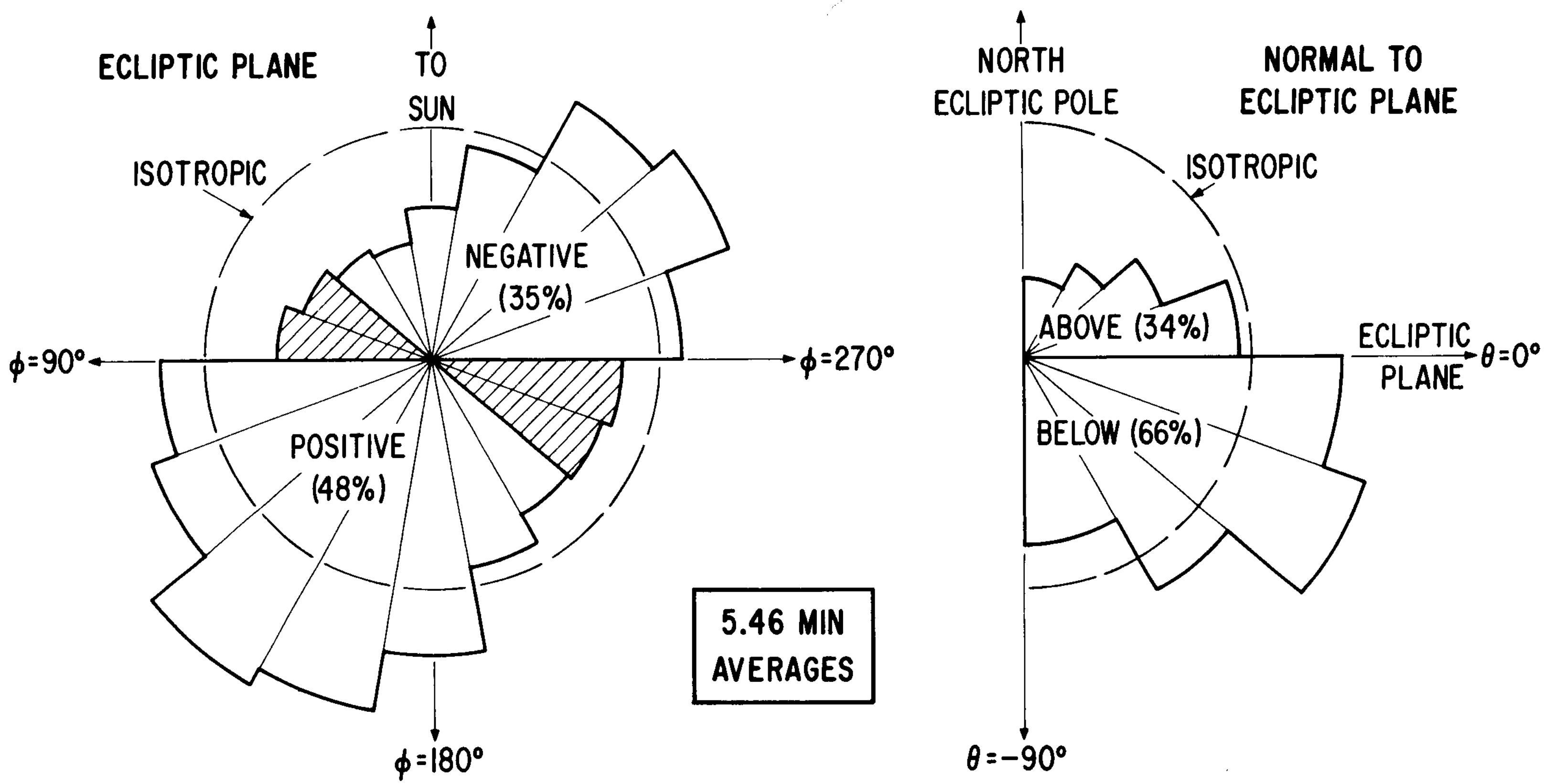
MARINER 2
COMPOSITE POWER SPECTRUM
B_r
• AVERAGE VALUES FROM LF HR SPECTRA FOR 10-DAY PERIODS BEGINNING ON DAYS 270 & 282
+ AVERAGE VALUES FROM HF LR SPECTRA FOR 1-DAY PERIODS BEGINNING ON DAYS 272, 274, 278, 282 & 283
A/F
C/F^2
POWER DENSITY $(GAUSS^2/CPS)$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
F_n
FREQUENCY $(F_n = 1.35 \cdot 10^{-2} CPS)$

FIGURE 3



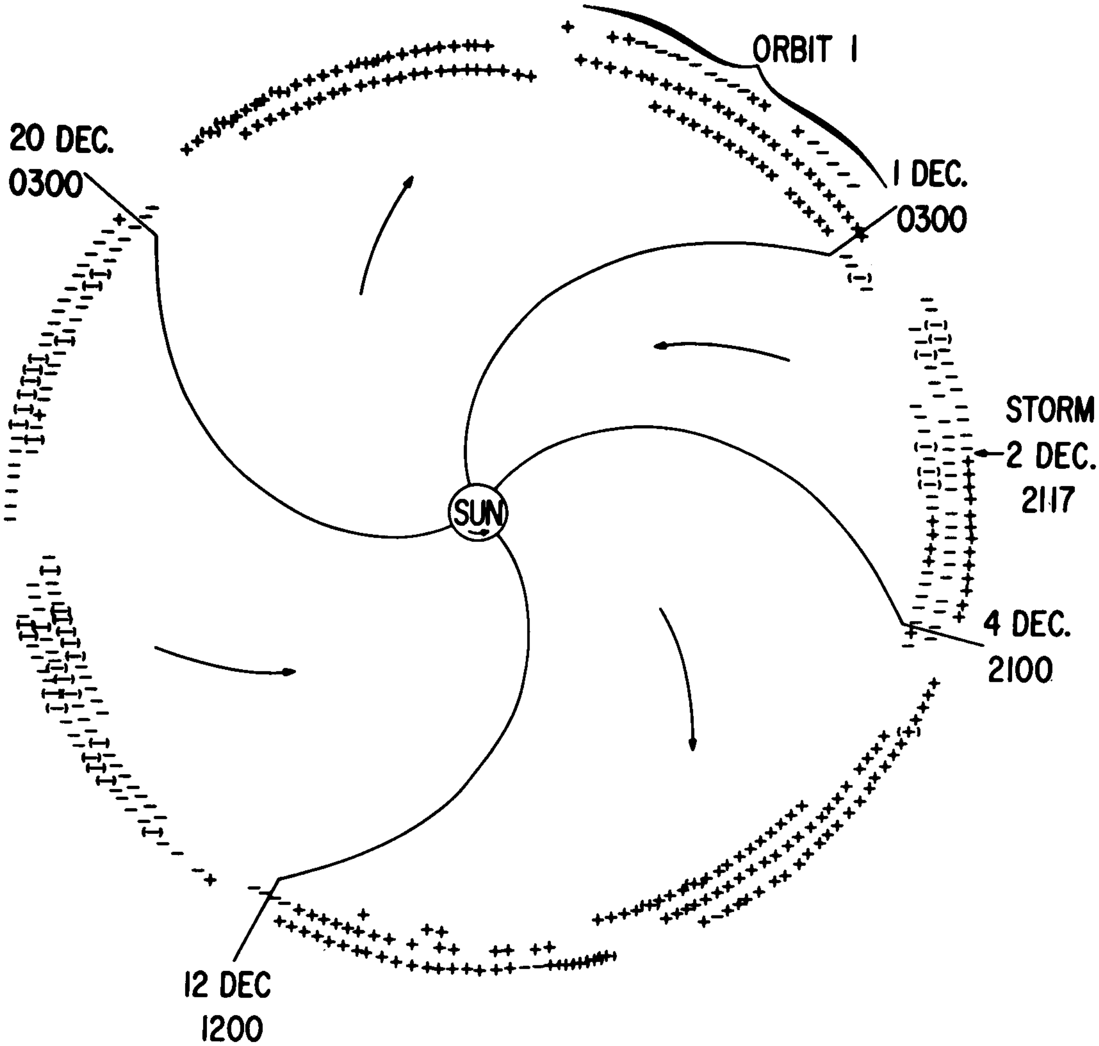
DISTRIBUTION OF INTERPLANETARY MAGNETIC FIELD MAGNITUDE

FIGURE 4



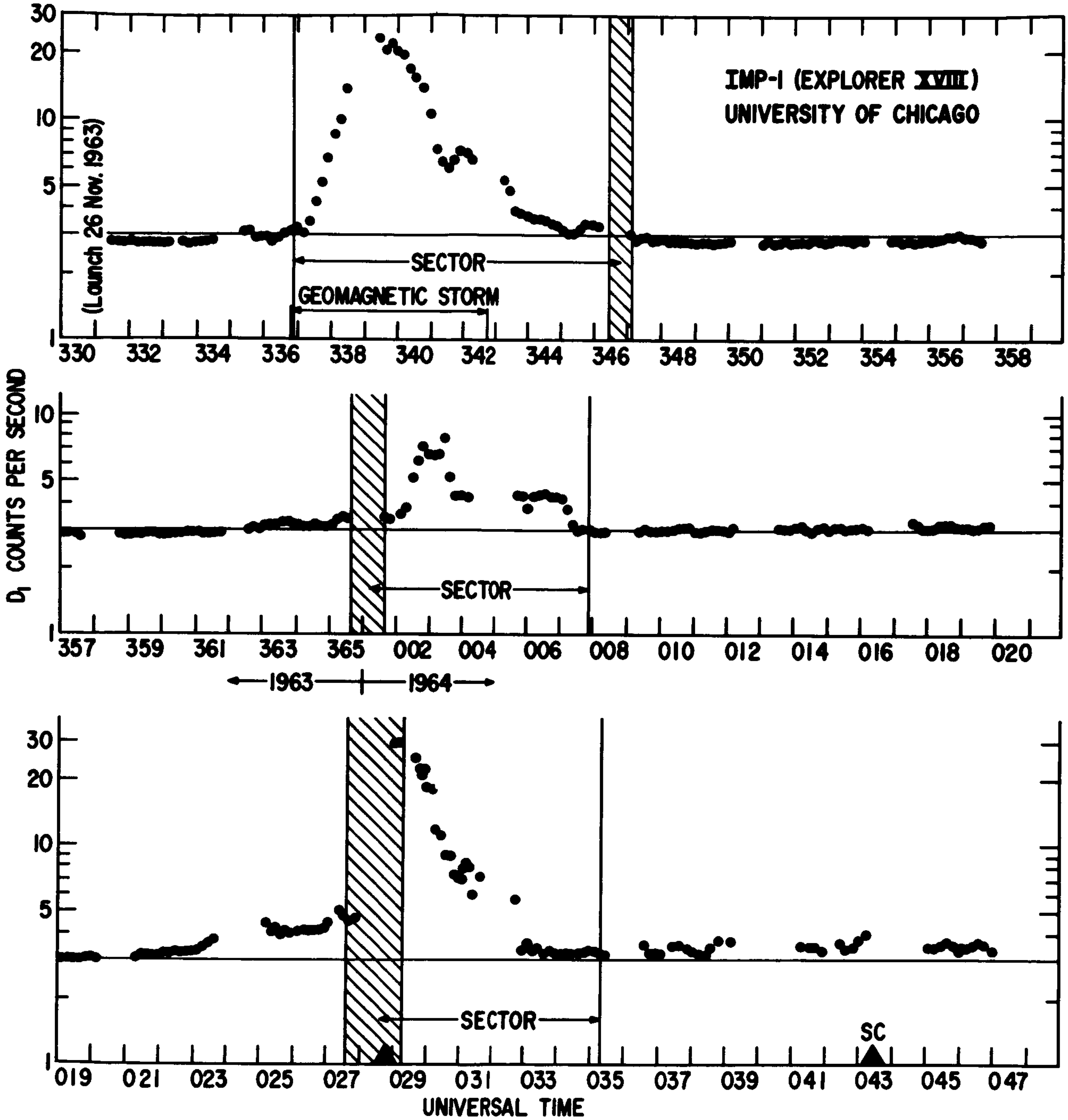
DISTRIBUTION OF INTERPLANETARY MAGNETIC FIELD DIRECTION

FIGURE 5



ORBIT 1
1 DEC.
0300
STORM
2 DEC.
2117
4 DEC.
2100
12 DEC
1200
20 DEC.
0300
SUN

FIGURE 6



IMP-I (EXPLORER XVIII)
UNIVERSITY OF CHICAGO
(Launch 26 Nov. 1963)
SECTOR
GEOMAGNETIC STORM
D1 COUNTS PER SECOND
SECTOR
1963
1964
SECTOR
SC
UNIVERSAL TIME

FIGURE 7

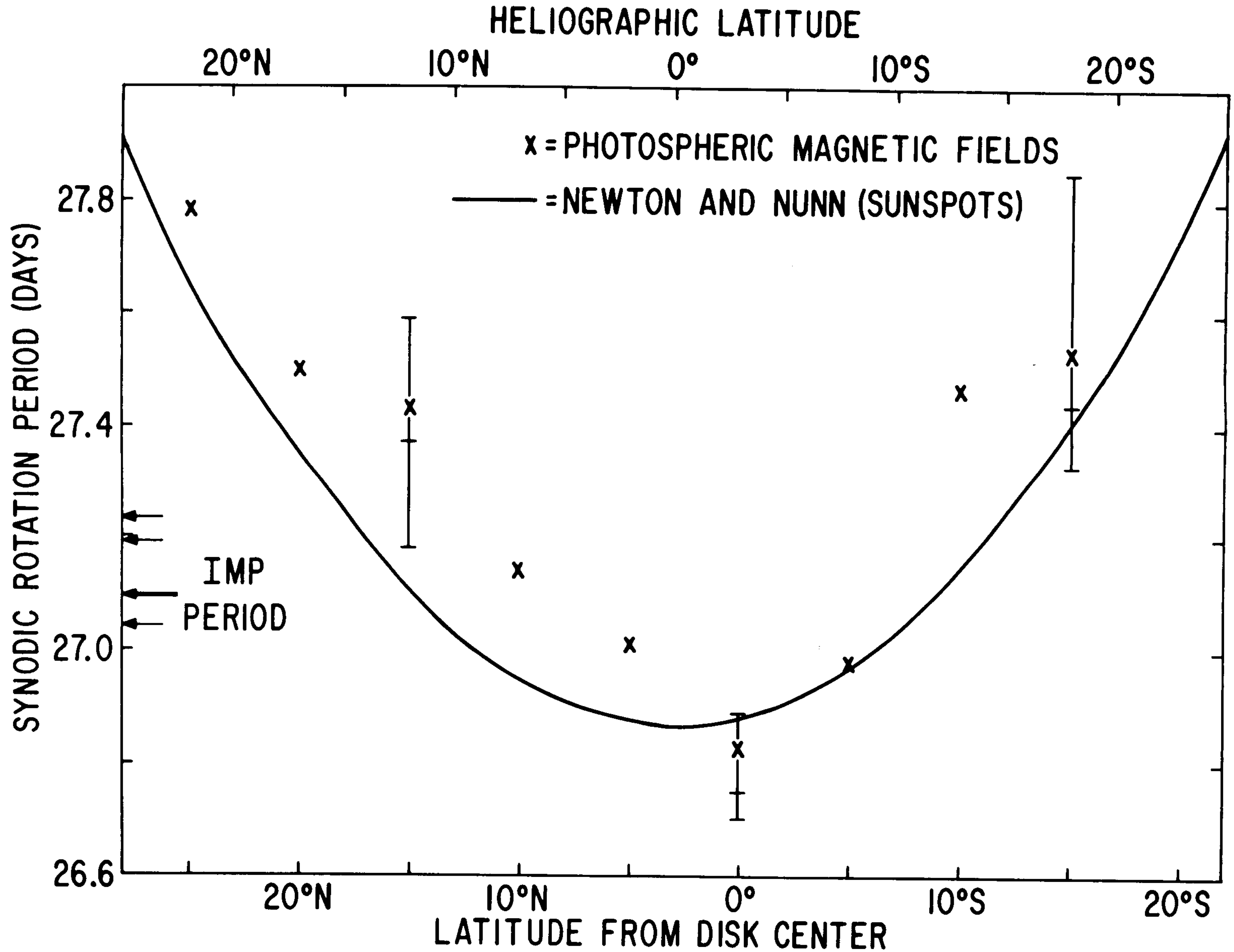

HELIOGRAPHIC LATITUDE
20°N
10°N
0°
10°S
20°S
x = PHOTOSPHERIC MAGNETIC FIELDS
= NEWTON AND NUNN (SUNSPOTS)
SYNODIC ROTATION PERIOD (DAYS)
27.8
27.4
27.0
26.6
IMP
PERIOD
20°N
10°N
0°
10°S
20°S
LATITUDE FROM DISK CENTER

FIGURE 8

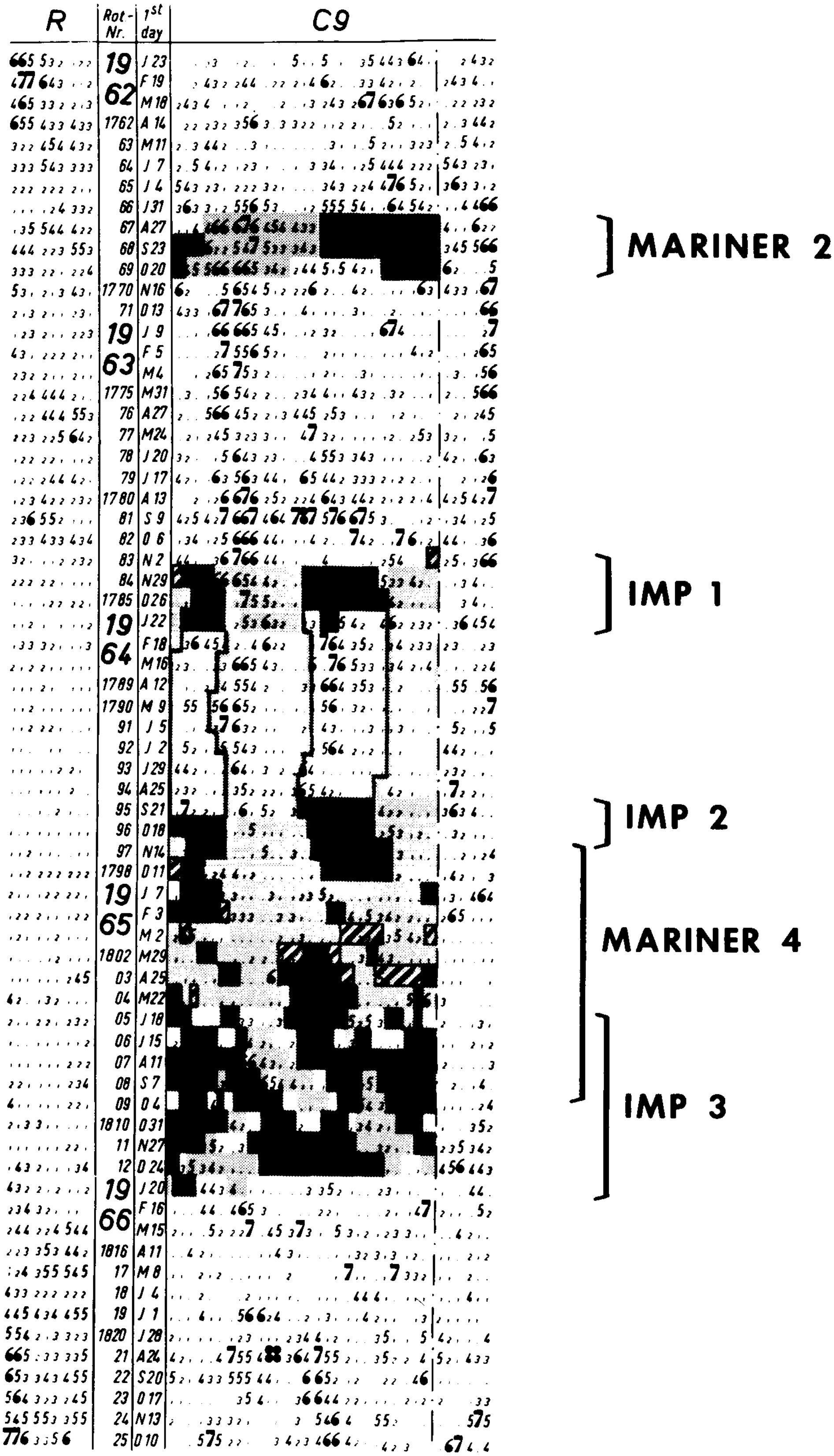
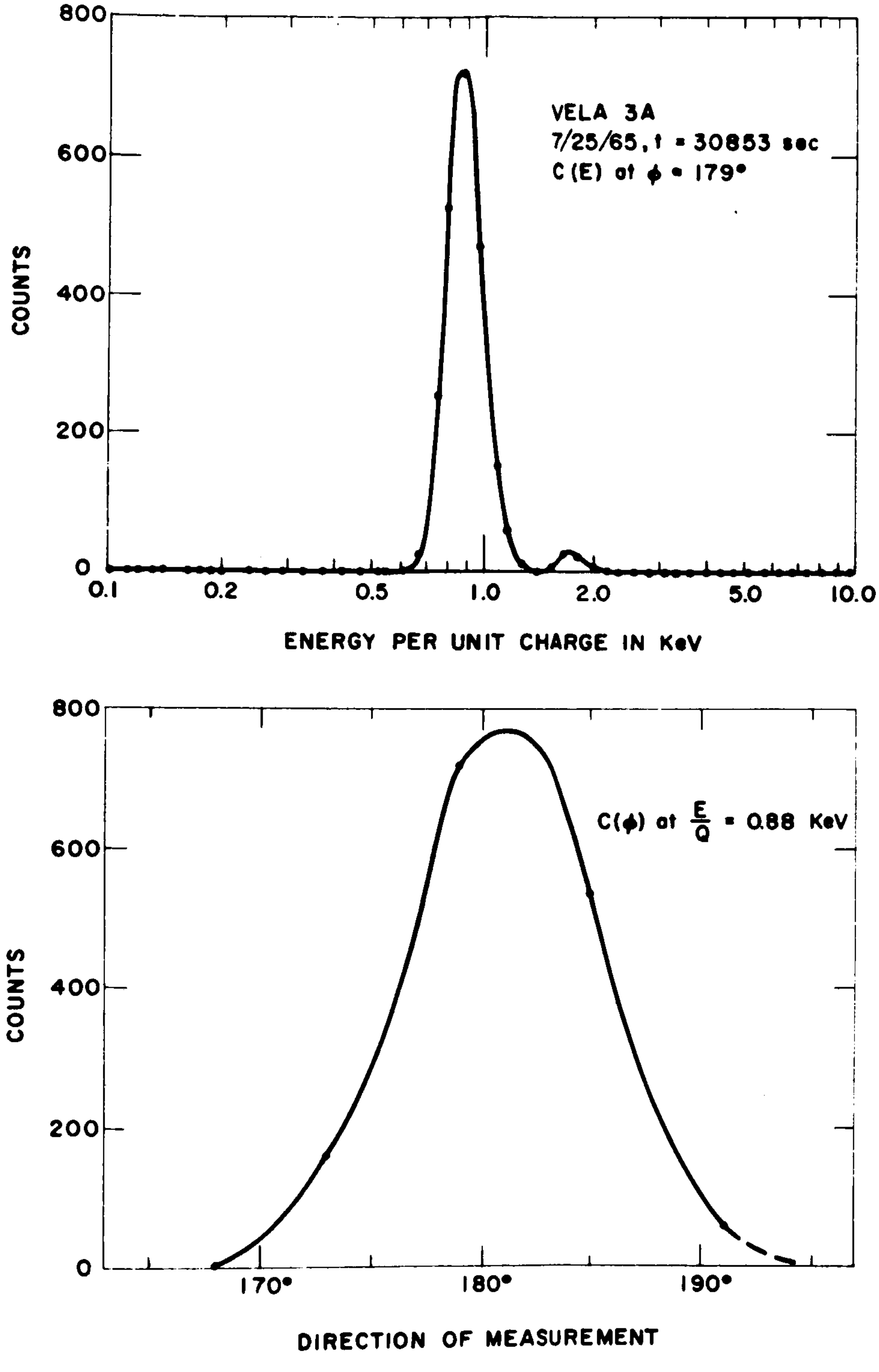


FIGURE 9



800
600
400
200
0
COUNTS
VELA 3A
7/25/65, t = 30853 sec
C(E) at φ = 179°
0.1
0.2
0.5
1.0
2.0
5.0
10.0
ENERGY PER UNIT CHARGE IN KeV
800
600
400
200
0
COUNTS
C(φ) at E/Q = 0.88 KeV
170°
180°
190°
DIRECTION OF MEASUREMENT

FIGURE 10

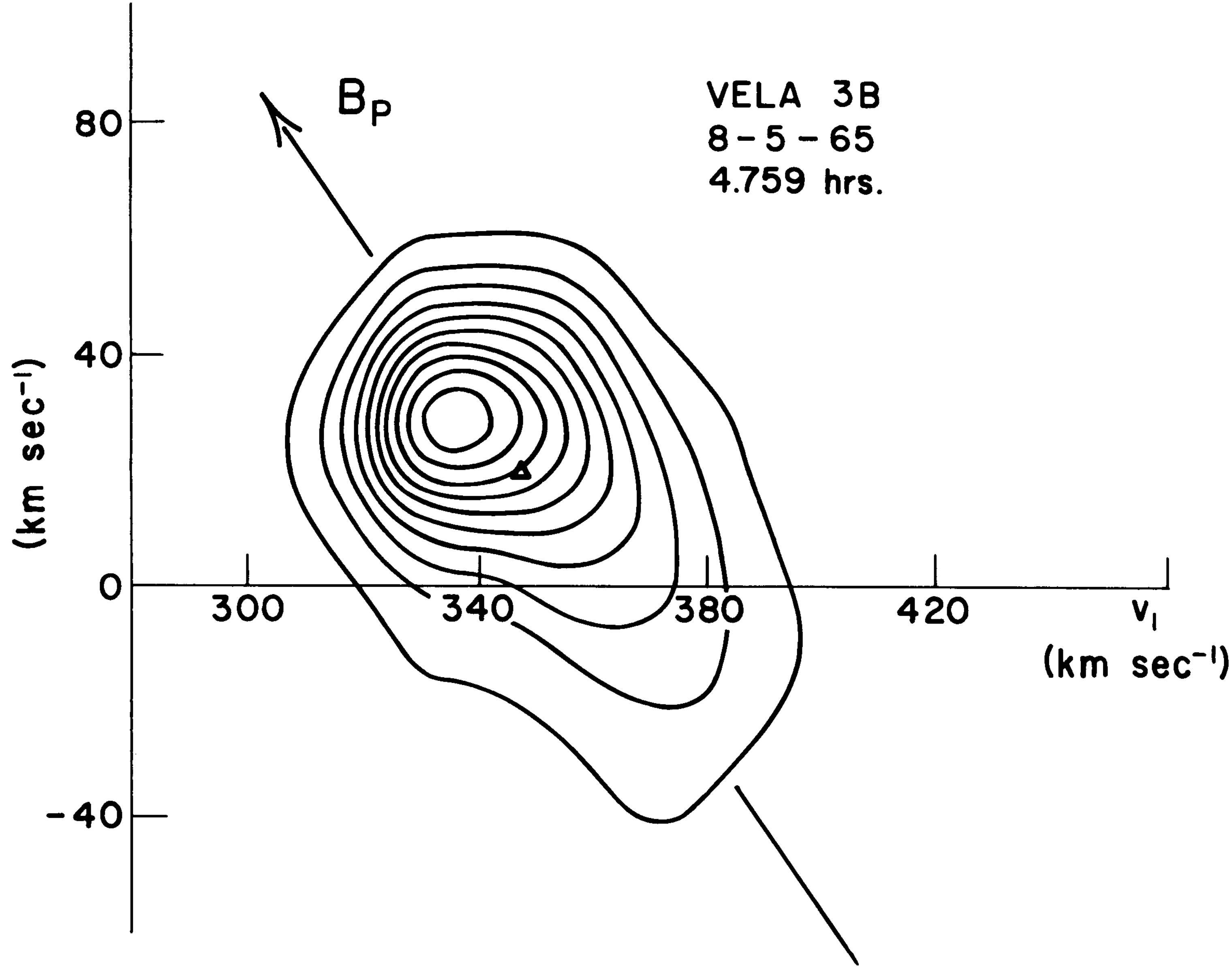

VELA 3B
8 - 5 - 65
4.759 hrs.
B_P
80
40
0
-40
(km sec⁻¹)
300
340
380
420
$v_\parallel$
(km sec⁻¹)

FIGURE 11

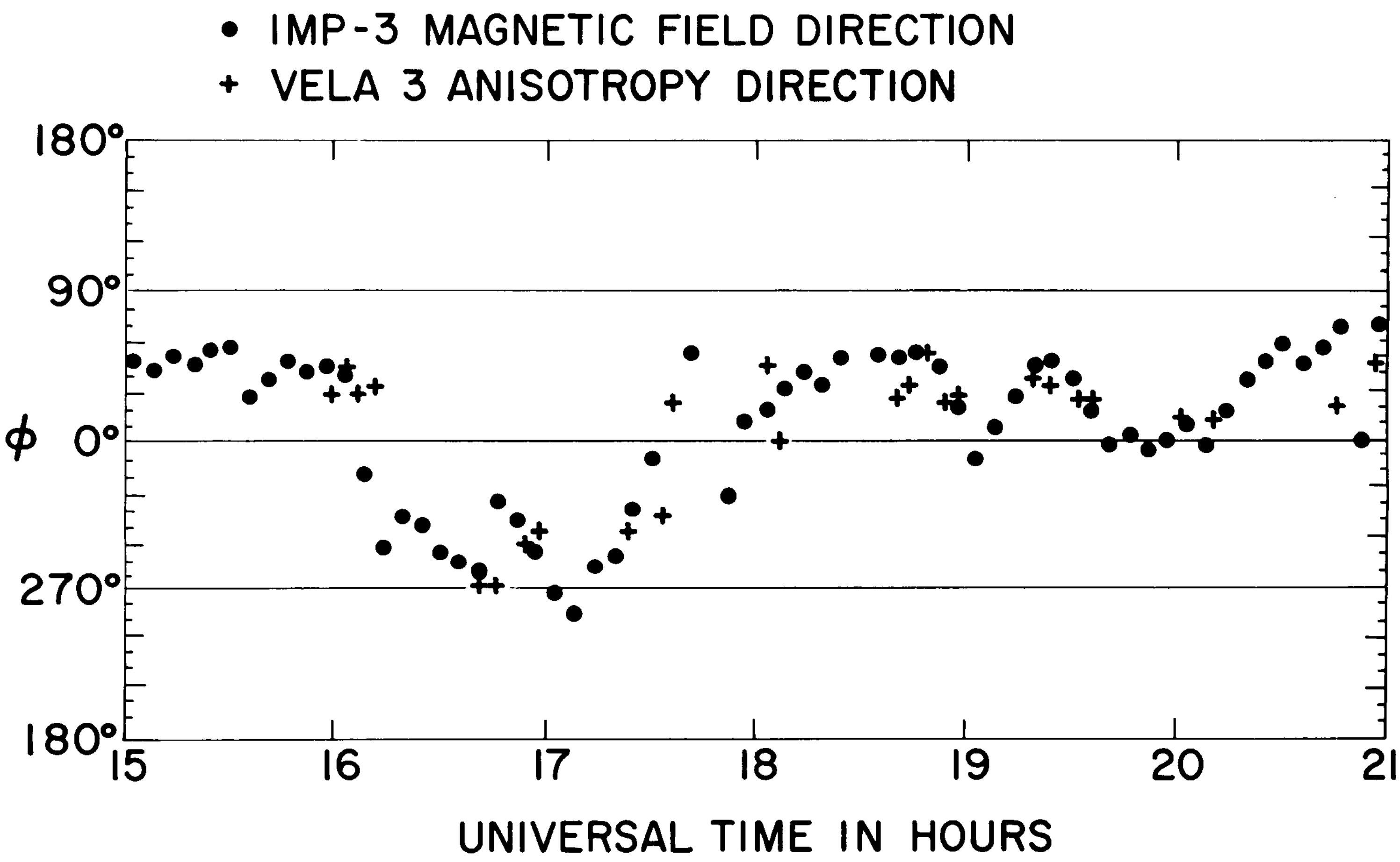
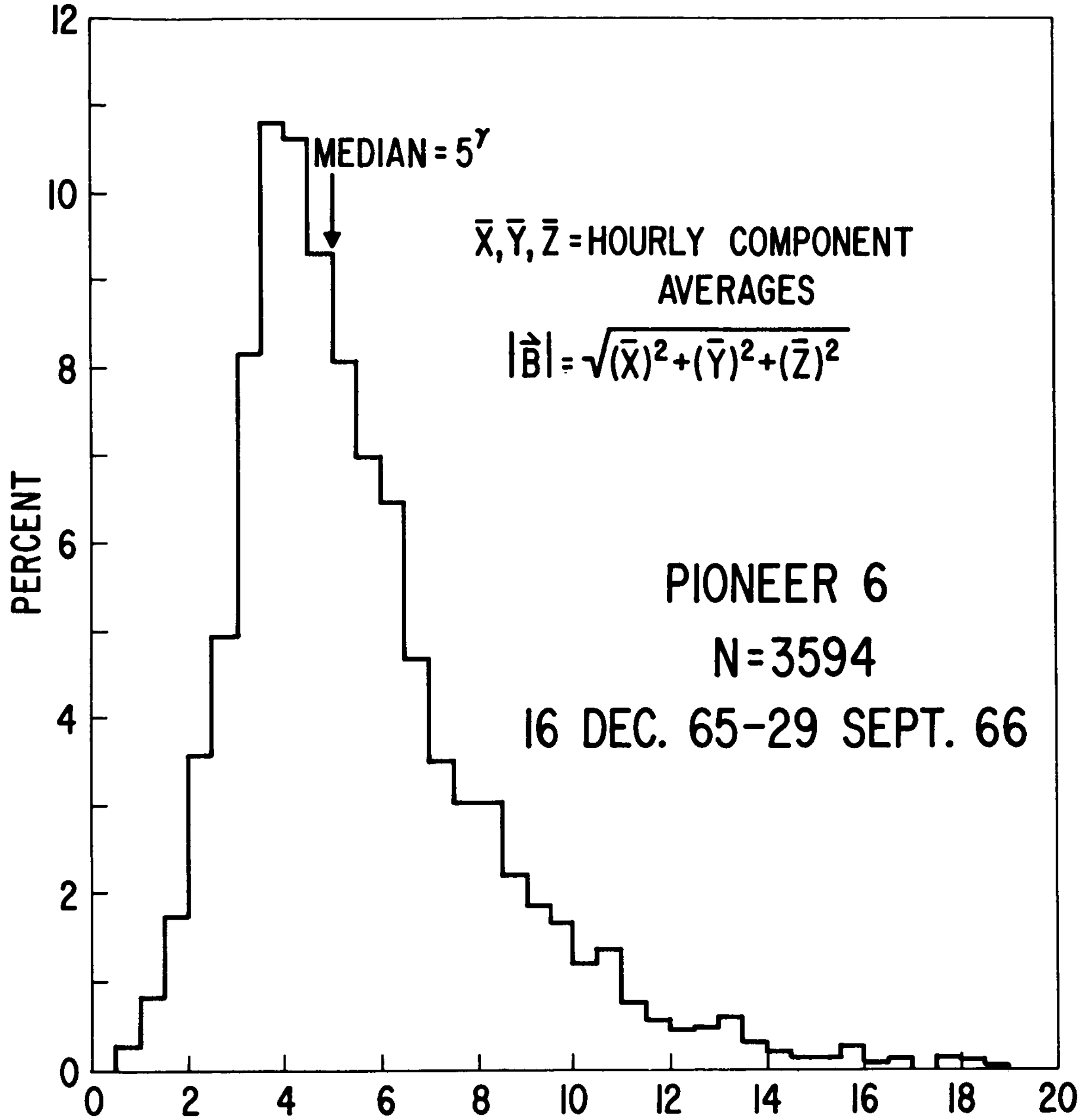
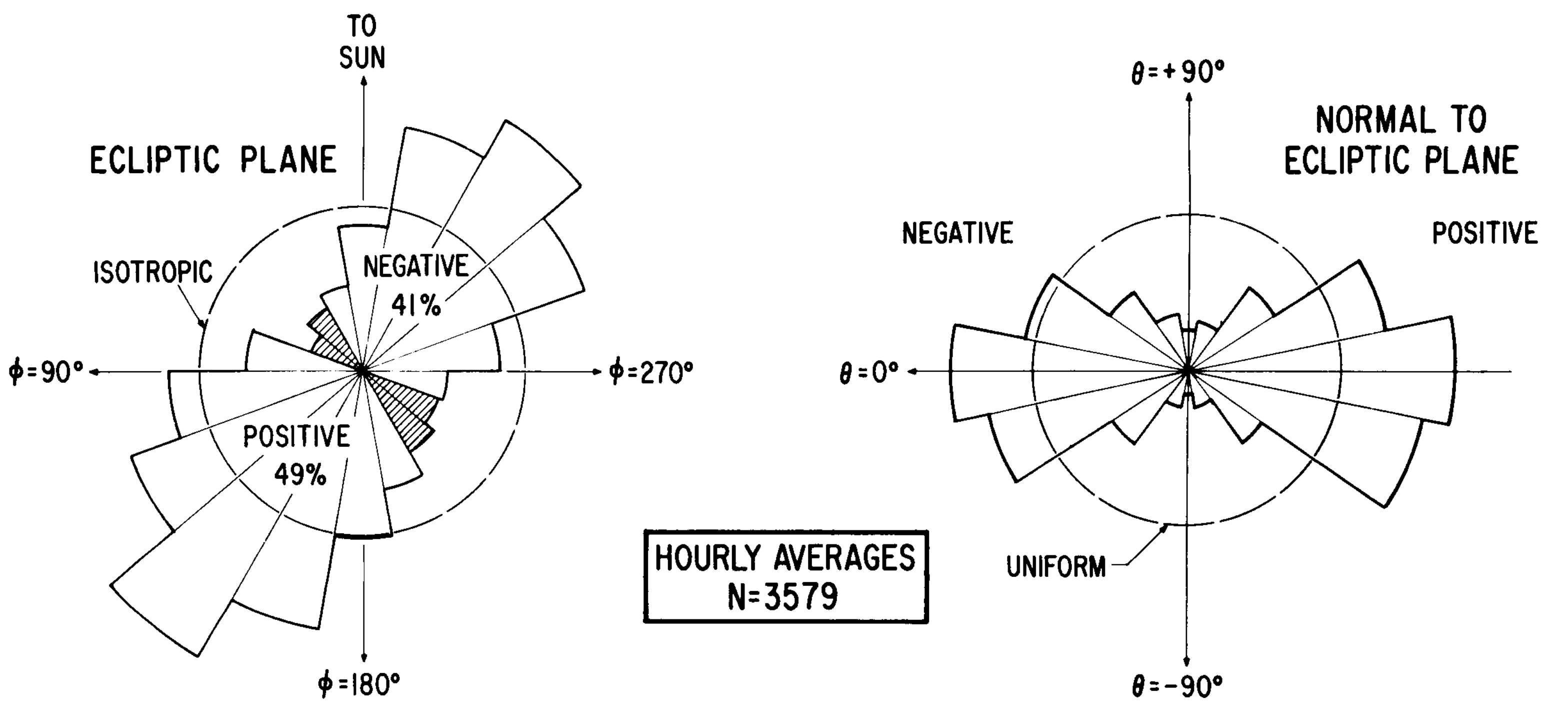

● IMP-3 MAGNETIC FIELD DIRECTION
+ VELA 3 ANISOTROPY DIRECTION
180°
90°
φ 0°
270°
180°
15
16
17
18
19
20
21
UNIVERSAL TIME IN HOURS

FIGURE 12



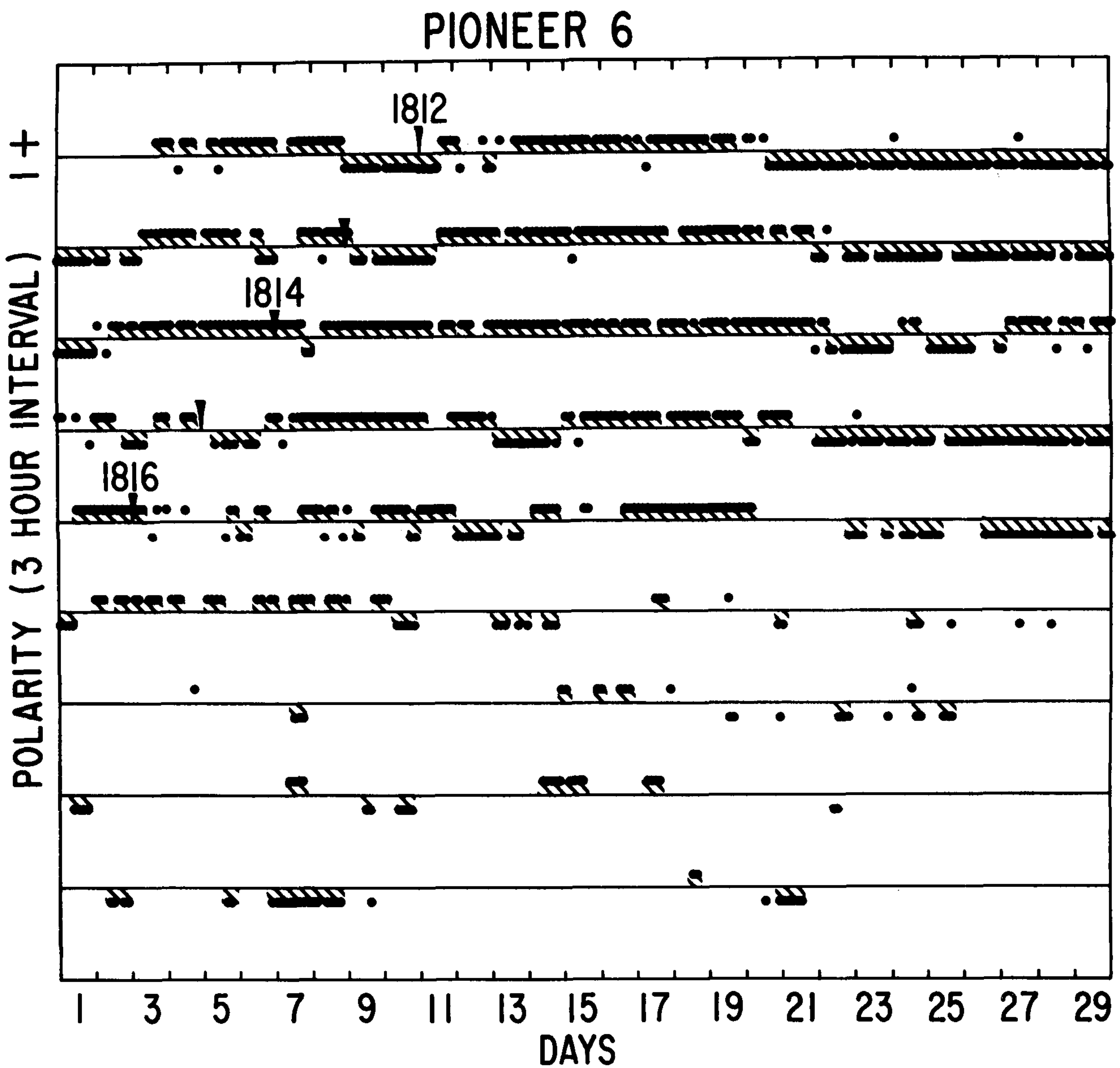
MEDIAN = 5^{γ}
$\bar{X}, \bar{Y}, \bar{Z}$ = HOURLY COMPONENT AVERAGES
$|\vec{B}| = \sqrt{(\bar{X})^2 + (\bar{Y})^2 + (\bar{Z})^2}$
PIONEER 6
N=3594
16 DEC. 65-29 SEPT. 66
PERCENT
0
2
4
6
8
10
12
14
16
18
20

FIGURE 13



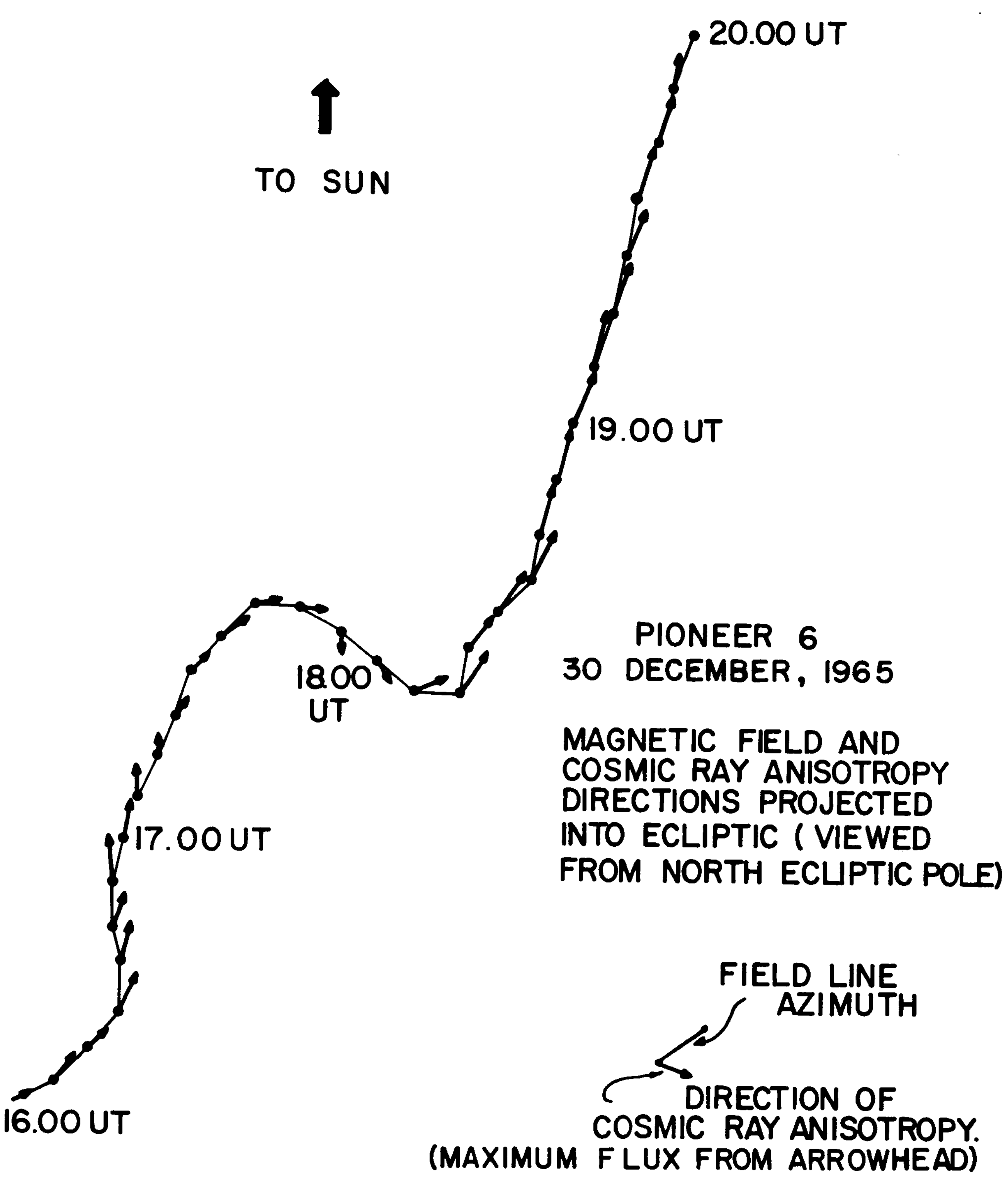
PIONEER 6, 16 DEC '65-29 SEPT '66

FIGURE 14



PIONEER 6
1812
1814
1816
+
−
POLARITY (3 HOUR INTERVAL)
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
DAYS

FIGURE 15



20.00 UT
TO SUN
19.00 UT
PIONEER 6
30 DECEMBER, 1965
18.00
UT
MAGNETIC FIELD AND
COSMIC RAY ANISOTROPY
DIRECTIONS PROJECTED
INTO ECLIPTIC (VIEWED
FROM NORTH ECLIPTIC POLE)
17.00 UT
FIELD LINE
AZIMUTH
DIRECTION OF
COSMIC RAY ANISOTROPY.
(MAXIMUM FLUX FROM ARROWHEAD)
16.00 UT

FIGURE 16

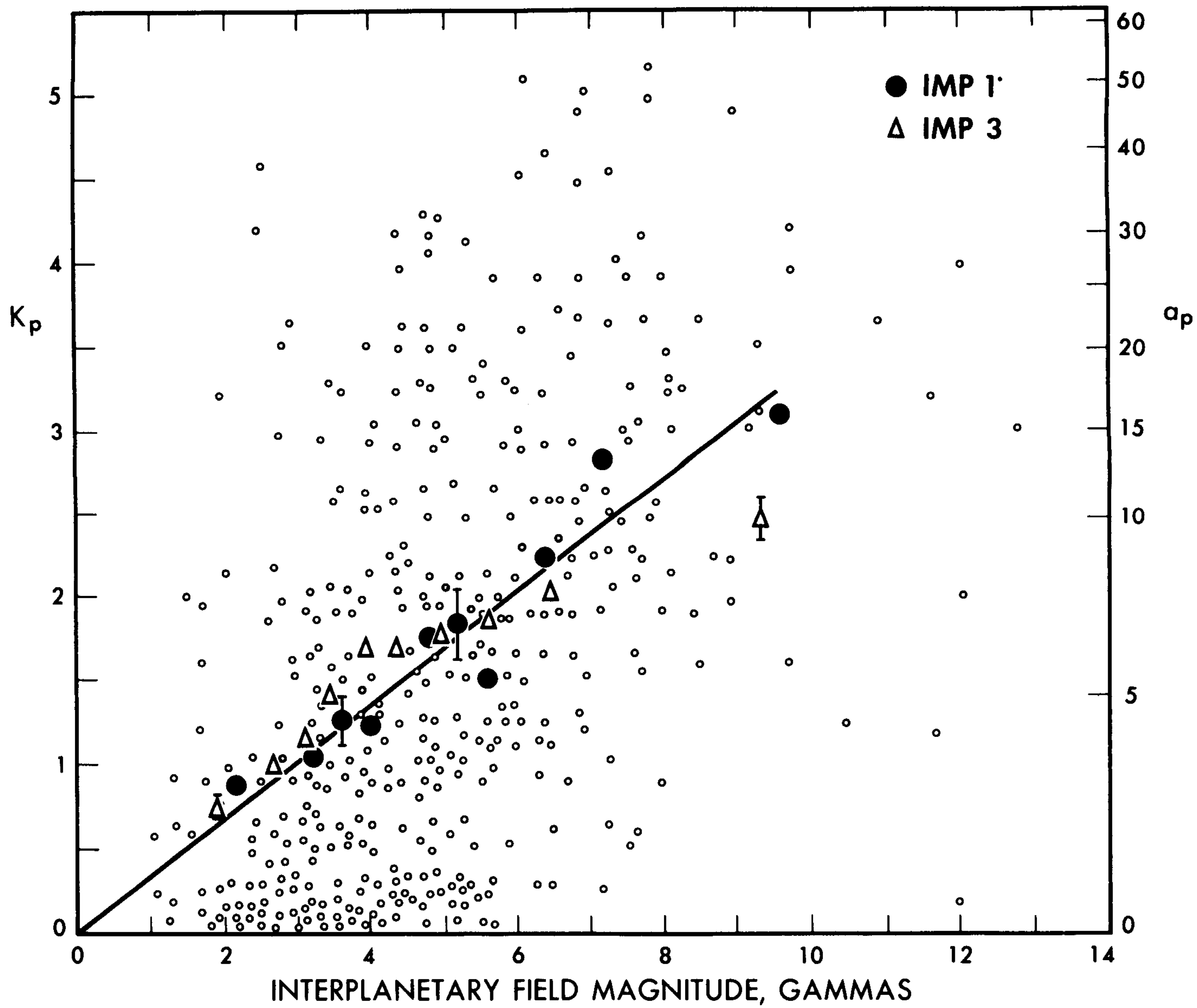


FIGURE 17